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Applying Sleep Modes in Legacy LTE Networks: An Energy-Efficient Study Based on Operator Data

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A B S T R A C T

This paper presents the design and evaluation of three practical sleep-mode mechanisms for improving the energy efficiency of legacy LTE Radio Access Networks (RANs). Motivated by empirical observations of persistent energy waste during low-traffic periods, and informed by site-level hardware constraints and inter-component dependencies, the proposed modes are tailored to operate within the limitations of existing infrastructure. Their design is based on power consumption data collected from a live operator network and builds upon an earlier optimization framework that identified the minimum number of active eNBs required to maintain full-service coverage. Using real PRB utilization traces from a commercial deployment, we simulate each sleep mode's impact on power savings and quality of service. Results show that substantial energy reductions of up to 18.2 kWh per site per day can be achieved without compromising connectivity, offering operators a flexible and realistic approach to energy-aware RAN operation.

Keywords: Sleep-mode design, empirical power modelling, component-aware deactivation, low-traffic optimization, legacy LTE deployment.

1. Introduction

As global mobile data consumption continues to escalate, the energy demands of wireless infrastructure have grown into a critical sustainability and operational challenge for mobile network operators (MNOs). In particular, the Radio Access Network (RAN) is widely recognized as the most energy-intensive segment of mobile networks, accounting for up to 80% of overall consumption [1]. Despite significant advances in 5G technologies, Long Term Evolution (LTE) networks continue to dominate coverage and traffic volumes worldwide, especially in developing regions where 5G deployment remains limited due to economic and logistical constraints [2], [3]. Consequently, energy efficiency in LTE RANs remains a central focus of both industrial and academic research agendas.

The disconnect between traffic load and energy consumption in legacy LTE deployments is well documented. Even during periods of minimal user activity, typically in the early morning hours, base stations (eNBs) exhibit limited power scaling, consuming close to peak-level energy despite significant reductions in Physical Resource Block (PRB) utilization [4], [5]. This structural inefficiency stems from hardware design limitations and rigid operational policies, where most components remain fully powered to preserve connectivity, despite the underutilization of resources. In response, industry standards such as 3GPP TR 36.927 [6] and recent white papers from leading vendors [7], [8] have advocated for energy-saving enhancements including sleep-mode operation, component-level scaling, and intelligent activation of RAN elements based on demand.

However, much of the research and implementation efforts in this domain remain either purely theoretical or simulation-based, lacking validation against real-world network constraints. While AI-driven dynamic control strategies have shown promise [9], they often require extensive training, continuous retraining in response to topological changes, and complex integration with legacy LTE infrastructure—factors that limit their deployability in operational environments, particularly in countries with constrained modernization budgets.

In our previous work [4], we conducted a comprehensive empirical study of energy consumption in a commercial LTE deployment, profiling component-level energy usage and identifying clear temporal patterns of underutilization. We established a linear power model correlating PRB utilization with instantaneous power draw and revealed that Remote Radio Units (RRUs) and baseband units are responsible for the majority of energy consumption, with idle site power averaging over 3 kW even during zero traffic. These findings underscored the need for more granular control mechanisms and informed our subsequent work [10], where we introduced an optimized eNB activation strategy based on spatial RSRP coverage and realistic path loss modelling. Through this, we demonstrated that under very low traffic conditions, as few as three carefully selected eNBs could maintain full-service coverage, substantially reducing the energy footprint of the RAN.

Building upon these foundations, this paper presents a practical extension: the design, implementation, and evaluation of three multi-stage sleep-mode mechanisms tailored for current LTE deployments. Our proposed mechanisms, the Light Sleep, Normal Sleep, and Deep Sleep modes, are informed by both empirical measurements and optimization results from our prior studies. Each mode targets a specific energy-performance trade-off, offering operators a practical toolkit to align energy consumption with traffic demand without compromising network stability or quality of service (QoS).

Unlike many studies that abstract away hardware constraints, our work acknowledges and integrates the realities of current RAN equipment. These include startup sequencing delays between MMUs, BBUs, and RRUs, inter-site dependency constraints (e.g., hub eNBs serving as backhaul gateways), and coverage overlap limitations. As reported by the operator involved in this study, any realistic sleep-mode strategy must explicitly account for these factors to avoid service degradation, coverage holes, or unintended isolation of remote eNBs. To that end, our sleep-mode schemes incorporate an energy-aware RRC (Radio Resource Control) mechanism that ensures robust UE-eNB association even in the presence of aggressive power-saving operations.

We assess the performance of the proposed sleep modes via event-driven simulations over a service area representative of a North African capital city. The simulation is grounded in a Poisson-disc-sampled deployment of 13 eNBs, uses actual PRB utilization data from the field, and integrates our empirically derived power model. The results demonstrate substantial energy savings, particularly with the Normal and Deep Sleep modes, achieving up to 90% power reduction during low-load periods with minimal impact on QoS metrics. We also extrapolate the findings to estimate potential national-scale energy savings, contextualizing the operational relevance of such schemes in regions grappling with frequent grid instability and rising electricity costs.

The contributions of this work are threefold:

1. **Design of Practical Multi-Stage Sleep Modes:** Each sleep mode is mapped to a specific operational profile and hardware configuration, incorporating reactivation delays, partial deactivation of components, and applicability thresholds based on traffic and coverage.
2. **Integration with Prior Empirical and Optimization Models:** The proposed mechanisms are built directly upon our previously validated power and coverage models, ensuring consistency and real-world relevance.
3. **Comprehensive Evaluation Under Realistic Constraints:** We simulate the application of these modes using real PRB load traces, validated propagation models, and operational assumptions from the target deployment, including UE distribution and inter-site dependencies.

The remainder of the paper is organized as follows. Section II outlines the system model, hardware architecture, and operational constraints. Section III introduces the three sleep-mode mechanisms in detail. Section IV describes the simulation setup and parameters. Section V presents results and analysis, including energy savings, blocking probability, and practical feasibility. Section VI offers a broader discussion, and Section VII concludes with future research directions.

2. System Model

This section presents the network assumptions, propagation and shadowing model, energy-aware eNB activation scheme, and the design of the proposed multi-level sleep modes. The model builds directly on the spatial signal framework and optimization methodology established in [10], and it integrates empirical power measurements from [4]. The sleep-mode logic and hardware dependencies are drawn from site inspection reports and deployment data provided by the operator.

2.1 Network Topology

We consider a 4.5 km × 4.5 km urban macro-cell deployment of M LTE eNodeBs, whose locations are represented as:

$$\mathcal{B} = \{b_1, b_2, \dots, b_M\}, b_i \in \Omega \subset \mathbb{R}^2 \quad (1)$$

Where Ω denotes the spatial service area. Site positions are abstracted using Poisson-disc sampling with minimum inter-site distance d_{min}, mimicking dense urban deployment constraints informed by the operator's guidelines. UEs are modelled as being uniformly distributed over Ω, in accordance with 3GPP simulation recommendations for macro-cell layouts [11]. Users are assumed to be stationary, which is valid for evaluating long-term energy efficiency under time-averaged load profiles.

2.2 Path Loss and Shadowing Model

The received power at a location x ∈ Ω from eNB_i is governed by large-scale path loss and spatially correlated shadowing. Following [10], we define:

$$\mathrm{RSRP_i(x)} = P_{tx} + G_t + G_r - L(d_{ix}) + \mathcal{X}_i(\mathrm{x}) - 10\log_{10}(120) \quad (2)$$

where:

- P_{tx} is the eNB transmit power, in dBm,
- G_t and G_r are antenna gains in dBi,
- $d_{ix} = ||b_i - \mathrm{x}||$ is the distance in km

- $L(d) = 128.1 + 37.6 \log_{10}(d)$ is the is the 3GPP UMa path loss model [11]:
- $10 \log_{10}(120)$ accounts for downscaling from total bandwidth to one Resource Block Group. This assumes 120 RBGs for a 20 MHz LTE carrier.
- $\mathcal{X}_i(\mathrm{x}) \sim \mathcal{GP}(0, \sigma^2)$ is a Gaussian shadowing field with exponential spatial correlation given by [12][13]:

$$\mathbb{E}[\mathcal{X}_i(\mathrm{x})\, \mathcal{X}_i(\dot{\mathrm{x}})\,] = \sigma^2 \, . \exp\left(-\frac{||\mathrm{x} - \dot{\mathrm{x}}||}{d_c}\right) \tag{3}$$

- σ is the standard deviation of shadowing,
- d_c is the spatial correlation distance,

UEs associate with the eNB that offers the maximum RSRP:

$$\text{serving}(\mathrm{x}) = \arg\max_{i \in \mathcal{A}(t)} RSRP_i(\mathrm{x}) \tag{4}$$

where $\mathcal{A}(t) \subseteq \mathcal{B}$ denotes the set of currently active eNBs at time t.

eNB Activation Strategy

The eNB activation strategy used in this work is directly inherited from [10], which formulates a combinatorial optimization problem to find the smallest subset of active eNBs that guarantees a minimum QoS threshold across the service area. The activation set is defined as:

$$\mathcal{A}(t) = \mathcal{B}_{core} \cup \mathcal{B}_{dynamic}(t) \tag{5}$$

where:

- $\mathcal{B}_{core} = \{b_i, b_j, b_k\}$ is the always-on triad, optimally selected to maximize spatial coverage under minimum load,
- $\mathcal{B}_{dynamic}(t) \subseteq \mathcal{B} \backslash \mathcal{B}_{core}$ are dynamically activated eNBs based on traffic load.

This selection guarantees full-area coverage during all operational states while enabling the remaining ten eNBs to transition into sleep modes as dictated by PRB utilization and time-of-day policies.

3. Sleep Mode Mechanism Design

This section presents the three proposed multi-stage sleep-mode mechanisms, each offering different energy-saving potentials aligned with hardware capabilities and deployment constraints. The design of each mode is grounded in empirical analysis, component-level power data, and practical observations gathered from the operator's network.

Rather than prescribing a specific control logic for their activation or deactivation, the sleep modes are introduced here as architectural templates that operators may apply according to their own traffic patterns, operational policies, and performance objectives. The simulation results presented later in this paper explore the **theoretical upper-bound potential** of these modes under ideal applicability conditions, thereby serving as a performance benchmark for future implementation strategies.

3.1 Design Constraints

Empirical evidence from our earlier study [4] shows that current eNB deployments exhibit substantial idle power draw due to rigid hardware configurations. Site components, including Remote Radio Units (RRUs), Baseband Units (BBUs), and Master Management Units (MMUs), exhibit strong interdependencies and require sequential startup in the following order:

$$MMU \rightarrow BBU \rightarrow RRU \tag{6}$$

These dependencies imply that full reactivation from a cold state may take up to 20 minutes, depending on the sleep depth. Additionally, operational concerns such as inter-site backhaul relays (HUB sites), startup failure risks, and QoS preservation impose practical constraints on how deeply and how often eNBs can be put into a sleep state.

To accommodate these realities, three distinct sleep-mode mechanisms are designed, each targeting a different energy-performance trade-off. The goal is to offer operators a range of sleep options that can be selectively applied depending on predicted traffic conditions, time-of-day windows, or anticipated idle durations.

3.2 Sleep Mode Taxonomy

The characteristics of the three proposed sleep modes are summarized below.

Table 1 – Proposed sleep-modes.

Sleep Mode	**Components Deactivated**	**Reactivation Time**	**Power Fraction**	**Use Case**
Light Sleep	RRU	< 3 min	30%	Short idle periods, fast wake-up
Normal Sleep	RRU + Baseband (BB)	6–8 min	20%	Scheduled low-load periods
Deep Sleep	RRU + BB + MMU	15–20 min	10%	Overnight or highly predictable

These modes are designed in recognition of several implementation constraints:

- **Startup dependencies**: More components deactivated implies longer reactivation delay.
- **HUB site exclusion**: Sites responsible for backhaul to other eNBs (HUBs) should not be placed in deep sleep.
- **Always-on core**: To maintain spatial coverage and service continuity, three eNBs are kept fully operational at all times. These were optimally selected in our previous work are eNB5, eNB6, and eNB9 [10].
- **QoS safeguarding**: Deep sleep is best reserved for traffic windows with demonstrably low demand and low variability.

Power Behavior Across Sleep States

The power model used here is derived from [4], where a linear regression fit was established between eNB PRB utilization and power draw. For active eNBs:

$$P_i(t) = P_{idle} + \beta \rho_i(t) \tag{7}$$

where:

- P_{idle} is the base idle power,
- β is utilization dependency constant,
- $\rho_i(t) \in [0, 100]$ is the is the instantaneous PRB utilization.

For inactive eNBs placed into sleep mode $s \in$ {Light, Normal, Deep}, the residual power is:

$$P_i^s = \gamma_s \cdot P_{idle}, \quad \text{with} \quad \gamma_s = \begin{cases} 0.3, & \text{for} \quad s = \text{Light} \\ 0.2, & \text{for} \quad s = \text{Normal} \\ 0.1, & \text{for} \quad s = \text{Deep} \end{cases} \tag{8}$$

The total RAN power at time t is then:

$$P_{RAN}(t) = \sum_{i \in \mathcal{A}(t)} (P_{idle} + \beta \rho_i\,(t)) + \sum_{j \in \mathcal{B} \setminus \mathcal{A}(t)} P_j^{(s_j(t))} \tag{9}$$

Where $s_j(t)$ is the current sleep mode of eNB_j.

4. Results and Analysis

This section presents the simulation results of the proposed sleep-mode mechanisms under a 24-hour weekday PRB utilization profile as per our previous work in [4]. The analysis includes power consumption trends, energy savings, and quality-of-service (QoS) indicators such as blocking probability. All evaluations are grounded in realistic operator deployment parameters and empirical load traces.

4.1 Simulation Configuration

The simulation models a dense urban macro-cell LTE deployment comprising 13 eNBs. Out of these, three core eNBs (eNB5, eNB6, and eNB9) remain active at all times to guarantee spatial coverage and backhaul continuity. These three have been chosen given our previous study in [10]. The remaining eNBs adopt one of the three sleep modes, depending on the simulated scenario. The resulting topology is illustrated in Fig. 1.

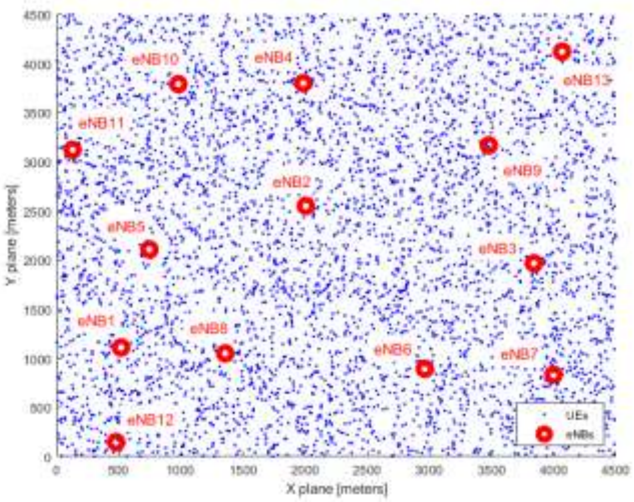

Fig. 1 - Service area; placement of eNBs and UEs.

An event-driven simulation is used to assess the potential of the application of sleep mode mechanisms. UEs arrive at the system with exponentially distributed inter-arrival times. File sizes are also exponentially distributed with an average size as described in Table 2. The results were averaged across 3 simulation runs, each run simulating 1 million file transmission trials. Users are stationary and no mobility is taken into account. This is a valid assumption for the scope of this work as the purpose is to evaluate network power requirements and this is dependent mostly on network utilisation regardless of UE possible dynamics.

Table 2 – Simulation parameters.

Parameter	**Value**
Service area	4.5 × 4.5 km² urban macro-cell
Core active eNBs	eNB5, eNB6, eNB9
Inter-site distance	≥ 750 m (Poisson-disc sampling)
UE distribution	Uniform [11]
Path loss model	$L(d) = 128.1 + 37.6\log_{10}(d)$ [11]
Shadowing model	Log-normal, σ = 8 dB, d_c=20 m [15]
Carrier frequency	2600 MHz
Average file size	1 [MB]
Bandwidth	20 MHz (120 RBGs)
Antenna gain / Tx power	15 dBi / 43 dBm
Idle eNB power (P_{idle})	3.1387 kW [4]
PRB Utiliz. dependency constant (β)	0.0147 [4]
Sleep-mode power fractions	Light: 30%, Normal: 20%, Deep: 10%

4.2 PRB Utilization Profile

In our simulations, a realistic PRB utilization is taken into account as illustrated in Fig. 2. The figure presents the average PRB utilization over 24 hours, aggregated from real data across five weekdays [10]. Utilization is lowest between 01:00 and 10:00, forming a natural window for sleep-mode applicability.

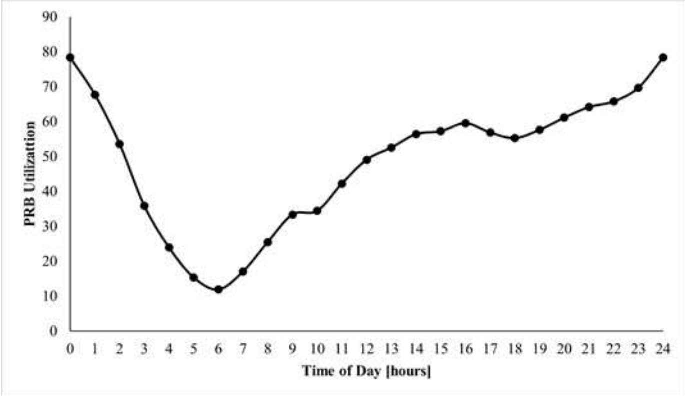

Fig. 2- Average PRB Utilization over Time of Day

The profile is typical of urban deployments in North Africa, with demand rising from midday and peaking after 20:00. The early morning low-load plateau is particularly suited for deeper sleep modes, while afternoon hours are better matched to light or no sleep transitions.

4.3 Numerical Results

Fig. 3 illustrates the mean instantaneous power drawn per eNB throughout the day under different sleep-mode configurations. All three modes achieve meaningful reductions during the 03:00–10:00 window. Light Sleep yields modest but safe reductions with fast recovery. Normal Sleep delivers greater savings, at the cost of longer wake-up periods. Deep Sleep achieves the lowest consumption (as low as 3.2 kW per site), though with the highest reactivation delay.

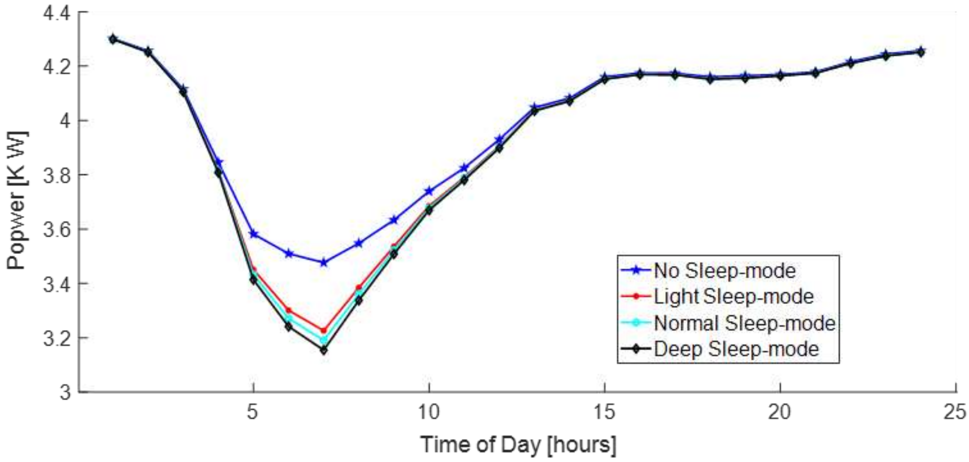

Fig. 3 - Instantaneous power requirements on average per eNB

The savings are especially valuable for operators in regions with unreliable electricity infrastructure, where offloading the grid during non-peak hours can enhance stability and reduce diesel generator reliance. To quantify long-term impact, Fig. 4 shows the total daily energy saved per eNB for each sleep mode.

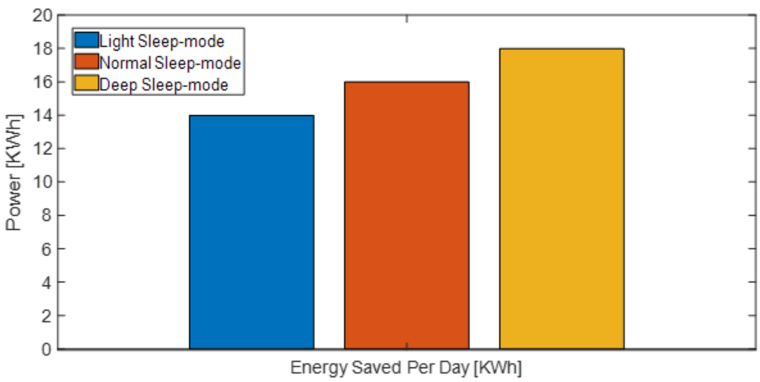

Fig. 4 - Potential energy savings per day [KWh]

- **Light Sleep:** ~14 kWh/day/site
- **Normal Sleep:** ~16.5 kWh/day/site
- **Deep Sleep:** ~18.2 kWh/day/site

Applied to a 13-eNB cluster, these savings scale to ~500 kWh/month in Normal Sleep, comparable to the monthly electricity usage of 34 typical Libyan households (average ~563 kWh/month per GECOL data [14]).

Operators deploying similar sleep strategies across national urban areas (~176,000 km² of populated territory [15]) could feasibly offset tens of gigawatt-hours monthly, reinforcing the strategic value of such mechanisms in national energy management policy.

Fig. 5 presents the average idle state probability of the eNBs across the day. This reflects the fraction of time each eNB is idle (i.e., not serving active traffic) and thus eligible for transition into a sleep mode.

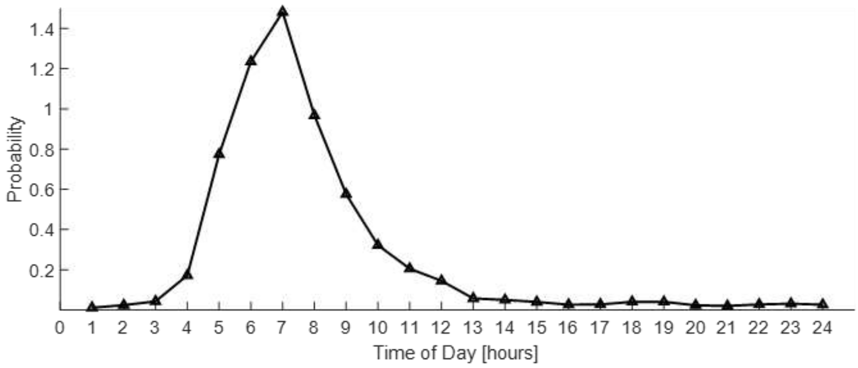

Fig. 5 - Average idle state probability of an eNB

The probability peaks between 05:00 and 09:00, aligning with PRB under-utilization trends seen earlier. This confirms the suitability of these early morning hours for applying deep or normal sleep modes, particularly for non-core eNBs that are not acting as HUB sites.

High idle probabilities translate directly into greater energy-saving opportunities, reinforcing the case for incorporating load-aware sleep-mode strategies into RAN operation.

Blocking probability reflects the proportion of UEs that experience resource contention or cannot be served due to capacity limitations. Fig. 6 plots this metric over time for each sleep mode.

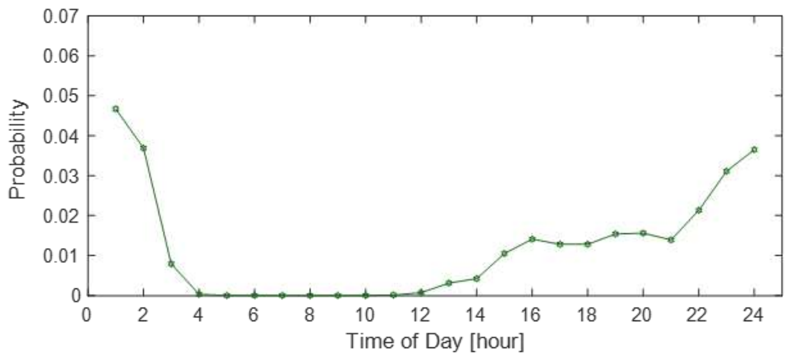

Fig. 6 - System QoS in terms of blocking probability.

Blocking remains below 5% across all modes and all hours, including early morning wake-up periods. Light Sleep incurs virtually no additional blocking. Normal and Deep Sleep introduce minor increases during transitions but remain within acceptable QoS margins.

This suggests that, with modest tuning or anticipatory scheduling, even deep energy-saving strategies can be compatible with real-world performance expectations.

5. Conclusion

This work evaluated the application of three practical sleep-mode mechanisms, Light, Normal, and Deep Sleep, on a real-world LTE RAN deployment. Using an empirically derived power model and validated eNB activation strategy, we assessed the impact of each sleep mode under realistic traffic patterns.

Results show that significant energy savings are achievable: up to 18.2 kWh per site per day in Deep Sleep, while maintaining acceptable QoS and uninterrupted coverage via a strategically selected always-on eNB core. The findings confirm that even in current LTE deployments with legacy hardware, targeted sleep-mode operation can offer substantial operational benefits without compromising service reliability.

These results provide operators with a flexible and deployable approach to improve energy efficiency, especially during extended low-traffic periods common in urban networks.

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